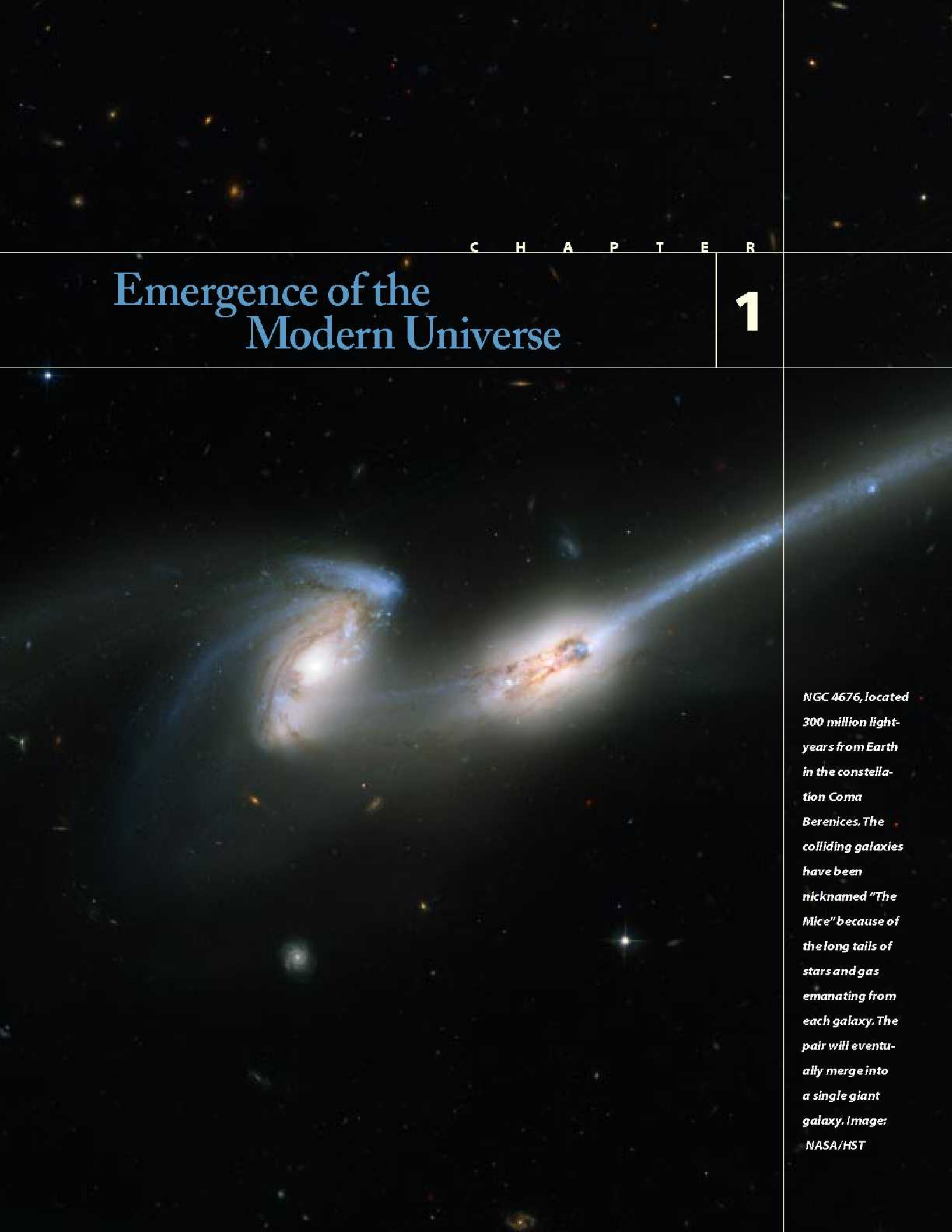


Emergence of the Modern Universe

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NGC 4676, located 300 million light-years from Earth in the constellation Coma Berenices. The colliding galaxies have been nicknamed "The Mice" because of the long tails of stars and gas emanating from each galaxy. The pair will eventually merge into a single giant galaxy. Image: NASA/HST

**...to understand how today's universe of galaxies,
stars, and planets came to be.**

Stars began to form even before the first galaxies, and what had been a calm, near-formless sea began to surge with the froth of complex forms of matter and energetic processes. Today the universe is full of structure, from the giant but simple galaxy to a minuscule but complex single living cell. Our objective is to understand how this came about, how stars and planets form, how the chemical elements are made, and ultimately how life originates.

In the 20th century we learned that our Milky Way Galaxy—a massive pinwheel of stars and gas bound by gravity—has been home to many generations of stars. Most of these billions of stars are likely to have “solar systems” of planets like our own—might they be home to billions of planets like Earth where life abounds? Only in the last few decades have we come to realize how closely bound our own existence is to the birth and death of these stars. Theoretical models of the Big Bang—the violent event that began the universe—describe an infant universe devoid of heavy elements such as carbon, nitrogen, oxygen, and iron that are essential ingredients of planet Earth and life itself. Where, then, did these essential heavy elements come from? It took decades of scientific research to discover how our Sun, along with every other “sun” that makes up our galaxy, manufactures heavy elements in the course of the nuclear fusion which powers it. In its death throes a star gently releases, or violently hurls, much of this material into space, where it can later collect to give rise to new stars further enriched with the building blocks of planets and life. This is the galactic ecosystem.

There is growing evidence that star formation began before there were galaxies, and that when these early stars died explosively as supernovae they

produced the first spray of heavy elements. But it also appears that the birth of galaxies, by binding the stars and gas together to create these cosmic ecosystems, was crucial to the buildup of heavy elements to a level where planets and life were possible. The emergence of such enormous structures from the near-featureless universe that preceded them, and the manufacture of vast amounts of heavy elements by their stars, were key steps on the road to life.

The modern era of the universe began, then, with the birth of stars and galaxies. Even as we work to trace the origins of the universe all the way back to the Big Bang, we recognize that our origins sensibly began later, some hundreds of millions of years after the Big Bang. In the billions of years since, complex chemistry and biology have evolved from the simple beginnings of the first stars and the first galaxies. Remarkably, astronomers can travel back through time to witness these crucial steps in our origins.

Our research will focus on two areas:

- How did the cosmic web of matter organize into the first stars and galaxies?
- How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?

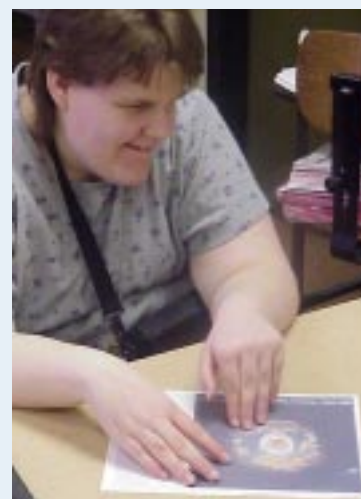
Touch the Universe: A NASA Braille Book of Astronomy

In an effort to serve students with special needs, a scientist and a Braille book author have used funding from the Hubble Space Telescope (HST) Cycle Education and Public Outreach (E/PO) grant program to develop *Touch the Universe: A NASA Braille Book of Astronomy*. Dr. Bernhard Beck-Winchatz, an astronomer at DePaul University in Chicago, wanted visually impaired students to experience the excitement generated by HST's beautiful images of the universe. When Dr. Beck-Winchatz received an HST research grant, he took advantage of the opportunity to apply for a supplemental educational grant to work with noted Braille book author Noreen Grice in creating a book of HST images accessible to visually impaired students.



Touch the Universe contains 14 spectacular HST images, each printed in color and supplemented by a transparent tactile overlay in which the color features are represented by tactile symbols. Through these images, the reader is taken on a journey of discovery to more and more distant objects, starting with images of the telescope itself in orbit and ending with the HST Deep Field image of some of the most distant galaxies in the universe. Accompanying explanatory text is given in both Braille and large print so that readers of all visual abilities are able to view and

read the book together. With plans for large-scale publication and distribution under way, the success of *Touch the Universe* indicates how a relatively small amount of money can result in a national product.





Research Area One

How did the cosmic web of matter organize into the first stars and galaxies?

Today's universe is full of structure—galaxies, stars, planets, and life. However, we now know that immediately after the Big Bang the distribution of matter and energy in the universe was almost perfectly smooth. Experiments such as BOOMERANG, COBE, and MAXIMA have measured very small irregularities—a thousandth of one percent—in the brightness of the cosmic microwave background, the vast sea of primordial radiation that shows us the universe at an age of a few hundred thousand years. Under the influence of gravity, the tiny fluctuations gradually built a weblike structure of mostly hydrogen gas and “dark matter” (whose nature remains mysterious) within which stars and galaxies would later form. A key program for the Origins theme is to provide a detailed account of how this happened.

Modern computer simulations suggest that the growth of structure advanced through the hierarchical mergers of dark matter concentrations—“halos,” as they are called. Eventually the gravity of the largest halos grew strong enough to pull in and concentrate the gas needed to build an infant galaxy. However, the first generation of stars may actually have preceded galaxies. With no heavy elements the cooling of the gas would have been very inefficient. Theorists have suggested that such different conditions would have led to a generation of short-lived stars, considerably more massive, hotter, and brighter than those we observe around us today. With their violent supernova deaths these first stars would have rapidly “polluted” the gas with heavy elements, thereby dramatically changing the climate for future star formation. The remnant black holes these supernovae likely left behind may have seeded the growth of supermassive black holes that powered the first quasars.

The energy in starlight comes from nuclear fusion reactions in the stellar core. However, a comparable amount of light comes from the release of gravitational potential energy as matter falls (“accretes”) into super-massive black holes at the centers of large galaxies. A quasar—the extreme manifestation of this process—can for a time outshine all the stars in its galaxy. The release of highly energetic photons from these first stars and quasars heated the gas and ionized it. We seek to understand how this happened, in detail, and how it affected the formation of later generations of stars and black holes. Ultimately, we want to know how all the relevant processes worked together to integrate gas, stars, and black holes into the dark matter halos to form the first galaxies. This means tracing the growth of dark matter halos, the distribution of gas in space and time, the synthesis of the heavy elements, and the buildup of stars and their remnants as the universe ages. A particularly important epoch lies between redshifts of 1 and 3 (from about 7 to 10 billion years ago), when the present-day universe began to take shape.

These questions lead us to pursue three investigations in this area:

- Study how pristine gas from the Big Bang condensed into the first generation of stars, and how their supernovae produced the first heavy chemical elements.
- Observe the enormous release of energy during the building of the first massive black holes that combined with energy from the first stars to change the structure of the early universe.
- Describe the assembly of galaxies and their subsequent evolution from generations of stars, leading to the diversity of galaxies in today's universe.

INVESTIGATION 1

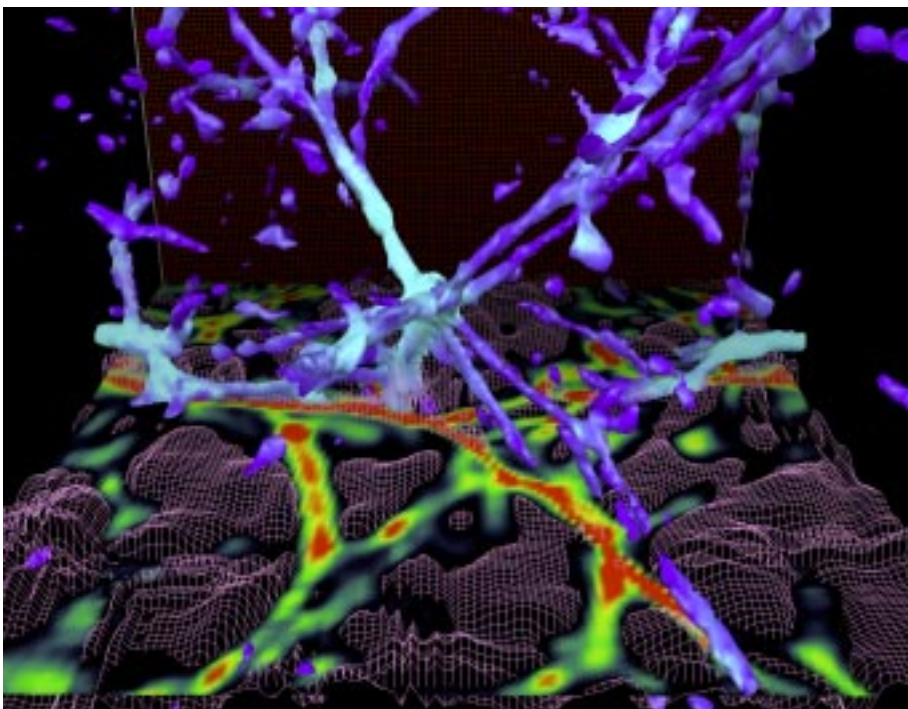
Study how pristine gas from the Big Bang condensed into the first generation of stars, and how their supernovae produced the first heavy chemical elements.

As the universe aged, gas was continually pulled into the dark matter halos. Over time, the pressure of the gas eventually came to be important and hydrodynamic effects began to compete with gravity in controlling the formation of galaxy-sized structures. The pressure in a gas depends partly on its temperature, influenced in turn by radiative cooling (depending sensitively on the history of heavy elements production by the first stars), and photoionization heating from the first stars and quasars. Shock waves would have formed in the supersonic infall of fresh gas into the dark matter gravity wells, further heating the gas. Gravitational tides exerted by neighboring structures would have applied torques to both the gas and dark matter, contributing to rotational support of the gas against gravity in these early protogalaxies. As the dark matter gravity wells coalesced and merged within the cosmic web, small protogalaxies collided and merged to form larger and larger structures—

this hierarchical description of galaxy formation is strongly supported by both theory and observation.

Understanding the formation of the first generation of stars will require continued theoretical modeling of the hydrodynamics, thermodynamics, and non-equilibrium chemistry of pristine hydrogen and helium gas in the evolving cosmic web of dark matter. Trace amounts of molecular hydrogen provide the dominant coolant of the gas in the initially smaller mass dark matter gravity wells with virial temperatures below 10,000 kelvin. The formation of this molecular hydrogen depends sensitively on the free electron abundance and therefore the exact ionization state of the gas. This in turn will evolve quickly once the first stars form. Larger dark matter wells with higher virial temperatures will have mostly ionized hydrogen and be able to cool much more efficiently. Detailed theoretical modeling of these processes, supported by the Origins Research and Analysis (R&A) program, will be required to make predictions to guide observations by Origins missions.

Direct detection of the first generation of stars will almost certainly require the unprecedented sensitivity of the James Webb Space Telescope (JWST). These stars are likely to be in clusters of approximately 10^6 solar masses.



Hydrodynamic simulation of the cosmic gas density at redshift 3, for a sample box 8 million light-years on a side. These dense filaments are detected as the Lyman-alpha forest in absorption-line spectra of distant quasars.



Artist's impression of the universe at age 1 billion years. The scene is dominated by starburst galaxies with bright knots of blue stars and hot bubbles from supernova explosions.

Very deep imaging of a single field with week-long exposures in multiple near-IR filters should be able to detect even modest birth rates of stars out to redshifts $z = 20$. Various spectral signatures will be able to test whether these are the very massive, hot, short-lived stars that theorists are now predicting, as opposed to a first generation with a full mass spectrum. JWST will also observe the first supernovae directly—these can be distinguished from starlight by their sudden appearance and slow decay. It should also be possible to investigate the dispersal of the first heavy elements by looking for the emission lines such as [OIII] predicted to be in the light from the earliest star forming regions.

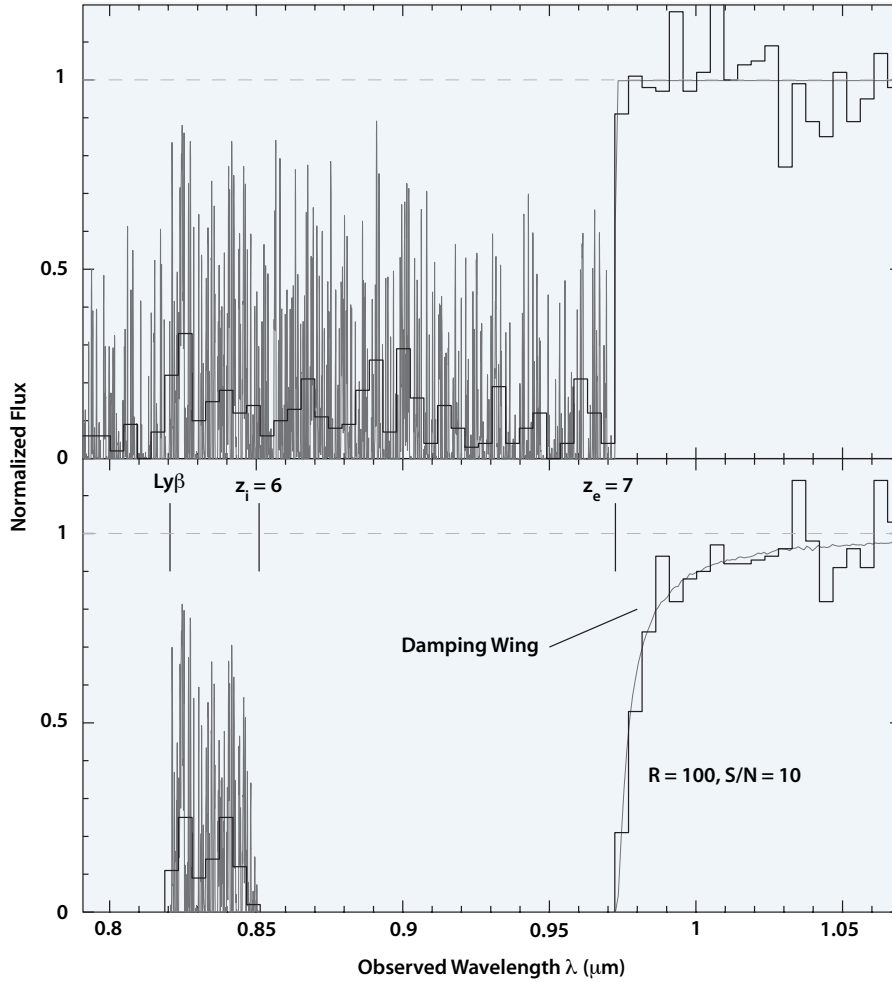
The epoch of the first stars and supernovae is not likely to be uniform throughout the early universe. In the denser pockets, we may find evidence that the birth of the earliest stars lies beyond our current observational reach. In other regions, we may discover pristine, primordial gas and direct evidence of the earliest star formation. Deep surveys by

JWST will provide an unbiased and statistically valid picture of the first epoch of stars and their chemical legacy.

INVESTIGATION 2

Observe the enormous release of energy during the building of the first massive black holes that combined with energy from the first stars to change the structure of the early universe.

Because they are so bright, quasars turn out to be the most distant (and therefore earliest) discrete sources of light that have been observed so far in the universe. Light from distant quasars is therefore routinely used to probe the evolution of gas between galaxies (the “intergalactic medium”). Spectroscopic observations by ground-based telescopes and the Hubble Space Telescope (HST) have used absorption by neutral hydrogen to trace the evolution of neutral gas in the cosmic web. Most of this gas is now ionized, however, whereas the very existence of the cosmic microwave background implies that electrons and hydrogen and helium



A simulated spectrum of the Lyman alpha forest in a quasar at redshift 7. The upper panel represents an extrapolation of the cloud statistics, and the lower panel shows the effect of increasing the cloud density beyond redshift 6: the reionization epoch.

nuclei combined to form neutral atoms early in the history of the universe. Something therefore reionized the intergalactic medium, almost certainly ultraviolet and/or X-ray photons from the first stars and quasars. This reionization heated the gas and altered its chemistry, thereby affecting its ability to accumulate into dark matter gravity wells and form later generations of stars and black holes. We do not yet know when this reionization epoch occurred, although there are tantalizing recent observations of the most distant quasars suggesting that the process may have been completed as late as redshift $z = 6$. We also do not know in detail how ionization occurred, and what were the relative contributions of starlight and quasars—JWST will be our primary investigative tool.

Massive black holes are now known to be ubiquitous in the nuclei of all large galaxies in the present day universe.

The masses of these black holes are tightly correlated to the larger scale random motions of stars in these galaxies, providing a clear indication that the structure of galaxies and the presence of black holes are intimately related. We do not know how this observed relation arose, and resolving the mystery will require observations of black holes in the process of formation. The optical and ultraviolet light from these earliest quasars will be redshifted into the near infrared (IR), and if dust enshrouds these objects then they will also be copious sources of mid-infrared radiation. Quasars can be distinguished from star forming regions because they also produce relatively greater quantities of X-rays. Deep imaging surveys across the electromagnetic spectrum are therefore the best way to search for and interpret these early sources. This is already being done with HST

and Chandra, but to push to the earlier epochs we will require high-sensitivity detections in the near-to-mid-IR. This next generation of surveys will begin with the Space Infrared Telescope Facility (SIRTF) and be carried to unprecedented depths by JWST.

Once the earliest sources are detected, JWST will use them as spectroscopic probes of the intervening intergalactic medium. Theoretical modeling of both quasar and galaxy formation, funded by the R&A program, will be crucial for interpreting this data. The exact time interval of hydrogen reionization will be determined with JWST through high signal-to-noise observations of the red damping wing of the Lyman-alpha absorption (Gunn-Peterson) trough in spectra of very high redshift sources. The shape of this damping wing can be used to directly measure the Lyman-alpha absorption optical depth and therefore the neutral hydrogen density. These and similar measurements will probe the evolutionary history of the gas, and provide a better understanding of the relative roles of stars and quasars during the reionization epoch.

This complex evolution is accompanied by ongoing star formation that illuminates the early protogalaxies. In addition, infall of gas into massive black holes produces quasars and less luminous active galactic nuclei (AGN). Observations of high redshift star formation and active galactic nuclei by HST and JWST will allow us to trace the buildup of galaxies with time. Dust formed by early generations of stars will also absorb and reradiate starlight and quasar light into the mid- and far-IR, making observations by SIRTF and JWST crucial to tracing the energy budget of galaxy formation and early evolution. Weak gravitational lensing of high redshift galaxies, observed with HST and eventually JWST, will be used to measure the mass distribution of foreground dark matter haloes. These observations can then be used to test theories of the evolution of the invisible framework of the cosmic web. JWST will be a powerful tool for the technique of gravitational lensing to chart the clustering of dark matter from galaxy halos to the much more massive galaxy-cluster halos.

The gas component of the cosmic web, for $z > 3$, would be observable in great detail with a next-generation ground-based telescope such as the Giant Segmented Mirror Telescope (GSMT). The enormous light-gathering power of such a telescope allows the use of faint galaxies as

the probes of intergalactic absorption. Unlike quasars, these background galaxies are sufficiently numerous to probe the cosmic web with the required resolution to see structure growth at the correlation length. The ability to follow the gas evolution of the cosmic web from $z = 3$ down to the present day will be greatly enhanced by the Cosmic Origins Spectrograph on HST, but a larger UV-optical space telescope, with far more efficient UV detectors, will be essential for a thorough understanding.

INVESTIGATION 3

Describe the assembly of galaxies and their subsequent evolution from generations of stars, leading to the diversity of galaxies in today's universe.

The buildup of the stellar component of galaxies will be measured with present and future surveys across a wide range of wavelengths, with HST, SIRTF, and JWST playing key roles. HST and SIRTF observations of young galaxies will measure star formation rates and the accumulation of older stars in these systems. A substantial fraction of star formation may be hidden by dust, and deep mid-infrared imaging by SIRTF will be able to detect dust-enshrouded star-forming regions out to $z = 2.5$, as well as possible dust-hidden AGNs. Complementary wide-field surveys in the near and mid-infrared will also be conducted by SIRTF in order to connect the evolution of galaxies with the growth of the large-scale structure that follows the evolution of the distribution of dark matter.

The deep JWST images designed to detect the first stars and quasars will also image large numbers of galaxies in the $z = 1 - 5$ redshift range that can be followed up with JWST and ground-based spectroscopy. Because of its much greater aperture, JWST will reach much fainter systems than HST and SIRTF, crucial for understanding the complete star formation history of the universe. JWST's spectroscopic capability will provide a powerful probe of the buildup of the heavy elements. Moderate-resolution spectroscopy ($R=1000$) in the rest-frame 3500–7000 angstrom range can be obtained for thousands of galaxies to provide a uniform sample of heavy element abundances, stellar ages, star-formation rates (from emission lines of HII regions), and measurements of the level of dust extinction. JWST spectroscopic observations of higher resolution ($R = 3000$),

possible for luminous galaxies, can measure stellar and gas kinematics and provide information on galaxy masses and further detail of the process of galaxy assembly. Spatially resolved spectroscopy of bright galaxies with interesting morphologies will probe the spatial variations in physical conditions in these systems. Complementary measurements for lower-luminosity galaxies over this epoch could be done with the next generation of larger ground-based telescopes (for example, the proposed 30-meter GSMT) using laser guide star adaptive optics and sufficiently high spectral resolution to overcome night-sky emission. Imaging and spectroscopy of high redshift galaxies in rich clusters, groups, and the field will provide the data needed to describe the effects of environment on galaxy formation and evolution.

The dust content of typical galaxies at high redshift is acknowledged as a vital and largely unexplored aspect of galaxy evolution. Observations with ISO and the SCUBA instrument on the James Clerk Maxwell Telescope have partially resolved the submillimeter background discovered by COBE into galaxies, providing strong evidence that much of the light generated by high redshift star formation is reprocessed by dust. SIRTf will undoubtedly detect more of the sources contributing to the background. JWST can measure even heavily dust-enshrouded star formation out to redshift $z = 3.5$ by detecting rest-frame 3.3-micron polycyclic aromatic hydrocarbon (PAH) emission. In addition, JWST can exploit numerous mid-IR spectroscopic diagnostics to distinguish star formation from hidden AGN. These include coronal lines of silicon, sulfur and calcium as well as rotation-vibration emission of molecular hydrogen.

The goal of this part of the Origins program is to understand how the first stars and black holes began the process of assembling the galaxies we see today. It will be essential to connect what we learn with observations of nearby galaxies. Measuring the rate at which stars formed at different times in the history of the universe will allow us to account for the integral population of stars and stellar remnants (white dwarfs, neutron stars, and black holes) that we observe around us today, as well as the overall abundance of heavy elements that were produced by these stars. Detections of high redshift supernovae and the determination of the variation in supernova rate with time will provide a

complementary measurement of the star-formation rate. Because certain classes of supernovae come from the most massive stars, this will also help us trace the rate at which stars of different masses form, which may help answer the question of whether the initial mass function of star formation is a function of environment and/or time. High-resolution spectral observations with ground-based telescopes of giant stars in Local Group galaxies can also provide a cross check to the yields of r- and s- process elements produced by different kinds of supernovae.

The stellar populations laid down in earlier epochs comprise the fossil record of stars in our own galaxy and its neighbors. The high spatial resolution of HST over a substantial field has been crucial for producing color-magnitude diagrams that, when combined with theory, validate the history of star formation that will be carefully charted with lookback observations of HST, SIRTf, and JWST. It will be important to extend our capabilities to larger apertures and higher spatial resolutions in order to reach other galaxies, to the main-sequence turnoff for the Milky Way's neighbors, and down to the giant and horizontal branches as far as the Virgo cluster. JWST will extend these studies beyond the reach of HST, but a larger HST descendant that images in the UV-optical would make a decisive contribution to this effort. Diffraction-limited, high-strehl-ratio imaging over modest fields would provide an essential, unique capability only achievable from space.

The morphology of today's mature galaxies is described by the Hubble sequence—a variety of distinct morphological types including irregulars, spirals and ellipticals—and these morphologies consist of basic structural components such as disks, bulges, bars, and spiral arms. There is now good evidence that the Hubble sequence arose between $1 < z < 3$, but as yet there are no observations to guide modeling of how the morphology and structures of galaxies arose and evolved. The high angular resolution and sensitivity of JWST will permit direct observations of the morphological evolution of galaxies as well as the history of galaxy collisions and mergers over this crucial epoch.



Research Area Two

How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?

Earth and its solar system siblings are made of ices from the carbon-nitrogen-oxygen family of elements and rocks from the calcium, silicon, magnesium, and iron groups. Life, as we know it, depends entirely on the complex chemistry of compounds built around carbon atoms, what we call “organic” compounds. We now know that the universe was not born with these materials, but that the stars themselves are the sites of their manufacture. This discovery—that the heavy elements essential for a living being come directly from stars—ranks among the greatest human achievements in understanding the universe and our place in it.

The buildup of these heavy elements did not happen all at once. We have learned how these elements are made in stars and how they can be recycled into future generations of stars and potential planetary systems. At the ends of their lives massive stars explode and less massive stars slowly shed gas enriched with these heavy elements. In each cycle the abundance of heavy elements increases as the “ash” of nuclear burning in the centers of stars is added to the mix. We now know that this enriched gas remains bound to a galaxy by gravity, at least for giant galaxies like our own, and that this store slowly increases over time. We can even roughly chart the increase in heavy elements over the generations of stars born over the 12 billion-year lifetime of our Milky Way Galaxy and compare it with the process in other nearby galaxies.

However, we know relatively little detail of the enrichment process for interstellar gaseous material in our galaxy and others. When and how did the process of chemical enrichment begin, and what kinds of influences regulated the process? What exactly is the importance of heavy elements (in gas,

molecules, and dust) for the formation of planets? Which elements are essential? For example, is there a minimum mass in long-lived radioactive elements needed for a geologically active planet such as Earth? Is there a threshold level of heavy elements necessary for planet formation? Do the abundance gradients in our own galaxy or others result in a “galactic habitable zone” where the formation of Earth-like planets is favored? Has the course of planet building changed over cosmic time as the abundance and balance of these heavy elements has grown? We can now begin to answer such questions by finding out whether the presence and character of planetary systems depends on the heavy element abundance of parent stars; for example, do stars with the lowest abundances, in the globular clusters of the Milky Way or in its outer halo, have well developed planetary systems? We can investigate whether the dust grains and complex hydrocarbons found in galactic clouds and star-forming regions survive to play a role in the formation of planets and their atmospheres, or whether instead they are vaporized in the process and remade in the later stages of planet building. Such studies will teach us how the development of giant star systems like the Milky Way is essential to the eventual emergence of life, how long our galaxy has been inhabited, and where we may look in our own galaxy to find other life.

We highlight two investigations in this area:

- Study how the lifecycles of stars in the Milky Way and other galaxies build up the chemical elements and galactic environments needed for planets and life.
- Observe when and where habitats for life emerged in the Milky Way and other galaxies.

INVESTIGATION 4

Study how the lifecycles of stars in the Milky Way and other galaxies build up the chemical elements and galactic environments needed for planets and life.

A galaxy may be thought of as a giant ecosystem containing stars, radiation, dust, gas, and planets. Much like ecosystems on Earth, the interactions among these elements are complex. As yet we know very little in detail about how galactic ecosystems work, and how they produce planets and life, but future Origins missions will shed much light on this process.

One of the least understood processes in the galactic ecosystem is the interaction between the stars and gas—massive stars and supernovae inject enormous amounts of mechanical energy through flows and shocks and by radiation into the gas. This stirs the gas and forms structures called superbubbles and fountains. Though these facts are clear, we have little understanding of the effect of this “feedback” on subsequent star formation and, hence, the buildup of heavy elements necessary for life.

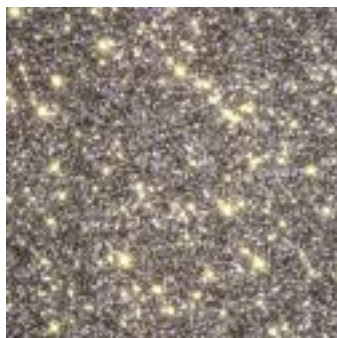
The full picture of star formation in the present-day universe will emerge only when we have studied the formation of stars in a sample of galaxies with a diverse range of mass, gas density, dust content and elemental abundance. SIRTf will, for example, characterize the large-scale infrared

properties of 75 nearby galaxies in order to correlate star formation rates with properties of the interstellar medium and JWST will extend such work to a far larger sample.

We also need to study how the star formation rates and elemental abundances of galaxies evolve over time, by looking at samples of galaxies at different cosmic distances (that is, at different look-back times). This will give us insight into the conditions in our own galaxy 5 billion years ago when Earth was formed. Large ground-based telescopes such as GSMT will make crucial spectroscopic studies of stars that record the fossil record of stellar birth in our galaxy and its neighbors to compare with the results of these lookback studies. The external environments of galaxies also play an important role in star formation. Galaxies rarely evolve in isolation—galactic ecosystems are not “closed boxes”—and mergers of galaxies affect their gas content, star formation rate and structural evolution. Galactic winds and the infall of clouds of gas and dust into large galaxies also act to modify the elemental abundances of the intergalactic medium and the interstellar medium in galaxies. We know that galaxies underwent many more mergers in the past, so we need to study galactic environments as a function of look-back time. This work will require large aperture telescopes and sensitive spectrographs operating from the UV to IR. These investigations will be enabled by JWST, Single Aperture Far-Infrared Observatory (SAFIR), and a HST

The nearby galaxy NGC 4214 is lit up by filigreed clouds of glowing gas surrounding bright stellar clusters. Their hot blue stars eject fast stellar winds, moving at thousands of kilometers per second, which plow out into the surrounding gas.





*Hubble Space
Telescope image of
the center of the
globular star cluster
Omega Cen. The very
high density of stars
makes this an ideal
laboratory for
studying interactions
among stars.*

descendent. Measurements of absorption lines in the spectra of background X-ray sources by Chandra and Constellation-X will also measure heavy element abundances in the interstellar media of galaxies, independent of whether these elements exist in the gas phase or are locked up in solid dust grains.

INVESTIGATION 5

Observe when and where habitats for life emerged in the Milky Way and other galaxies.

Our solar system orbits the galaxy at a distance of roughly 24,000 light-years out from the center; currently it is the only known system to contain life. Is our location a coincidence, or is this region of the galaxy more hospitable to the formation and evolution of life? In other words, is there a galactic habitable zone much as there is a habitable zone around a star? Sampling from the central regions of our galaxy to its periphery, both star formation rates and heavy element abundances are seen to decrease. It is conceivable that there is a minimum heavy element abundance necessary for the formation of both terrestrial and giant planets as well as for life, and that this abundance does not exist in the outer regions of the galaxy. It is also possible that various mixes of heavy elements, particularly radioactive ones, are important for the formation of a world with plate tectonics, and that this is important for the evolution of life. Recent studies

have shown that the mix of different heavy elements has changed dramatically over the history of the Milky Way and, by implication, for other galaxies as well. By investigating the incidence of planets and, ultimately, life, in various regions of our galaxy we will be able to determine the necessary galactic environmental conditions for the formation of planets and life.

Such investigations have already begun. An extensive observational search with HST for planetary transits of stars in the ancient globular cluster 47 Tucanae turned up no planets, even though the search had considerable sensitivity. Could it be that the low heavy element abundance of globular clusters precludes the formation of planets, or might encounters between neighboring stars in such dense stellar systems disrupt planetary systems or prevent them from forming in the first place? Future observations and theoretical investigations within the Origins program will address such questions as how the presence of terrestrial and giant planets is related to stellar mass and age, magnetic activity in the star, binarity and/or the presence of surrounding stars in a cluster, and the overall galactic environment in which the star formed. For example, SIRTf, JWST, and eventually next-generation near-to-far-IR space telescopes will be able to observe planet formation in a wide range of environments.

These modest studies are only the beginning. In the far future one can imagine extending some elements of the search for planets beyond our own galaxy. For example, can observations of infrared emission from young stars in dwarf galaxies with low abundances of heavy elements tell us, by analogy to similar, higher resolution and higher sensitivity observations of Milky Way stars, whether such galaxies could have planets and life? More extensive studies of their histories of star formation and heavy element abundances will tell us, in comparison with the Milky Way, whether planet building is likely to have proceeded differently in different types of galaxies. Through exhaustive study of the relatively nearby stars and detailed studies of the stellar populations far from our neighborhood, we may eventually connect the incidence of planets and the potential for life to the global properties of galactic environments.